

# Surface Acoustic Wave Microhygrometer

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## ABSTRACT

A microhygrometer has been developed at JPL's Microdevices Laboratory based on the principle of dewpoint/frostpoint detection. The surface acoustic wave device used in this instrument is approximately two orders of magnitude more sensitive to condensation than the optical sensor used in chilled-mirror hygrometers. In tests in the laboratory and on the NASA DC8, the SAW hygrometer has demonstrated more than an order of magnitude faster response than commercial chilled-mirror hygrometers, while showing comparable accuracy under steady-state conditions. Current development efforts are directed toward miniaturization and optimization of the microhygrometer electronics for flight validation experiments on a small radiosonde balloon.

## INTRODUCTION

Monitoring humidity is necessary for environmental control and process monitoring in space. NASA's Human Exploration and Development of Space Enterprise requires small, reliable, and accurate instruments for this application. Developed for *in situ* measurements in Earth and planetary atmospheres, the surface acoustic wave (SAW) microhygrometer is capable of extremely fast, accurate measurements of environmental humidity. In this paper, we describe the principles and performance of the SAW microhygrometer.

## WATER VAPOR IN EARTH'S ATMOSPHERE

Water vapor plays a crucial role in energy transport and chemistry in the Earth's atmosphere. *In situ* measurements of water vapor in the atmosphere are needed for studies of weather and climate, as both a primary data source and as ground truth for remote sensing measurements. Global coverage for these measurements is necessary to develop a more complete picture of weather and climate.<sup>1,2</sup>

Beyond these atmospheric measurements, water vapor is critically important in many technological applications. In spite of its importance, humidity measurement remains a difficult technological problem, and no single instrument or technique is optimal for all applications.<sup>3</sup> Part of the difficulty lies in the enormous range of conditions in which the instruments are required to operate. The water vapor concentration in the atmosphere ranges from several percent at the surface to parts per million in the stratosphere, while ambient temperatures vary over 100°C and ambient pressure drops several orders of magnitude from the Earth's surface to the upper stratosphere.

## HUMIDITY MEASUREMENT TECHNIQUES

Several instruments have been used for *in situ* measurements of atmospheric humidity. Balloon-borne radiosondes account for most of the *in situ* observations of atmospheric humidity. Sensors currently used on radiosondes, such as carbon hygristors and capacitive polymers, measure the relative humidity based on water vapor absorption into hygroscopic materials. Defined in terms of the mole fraction of water in a given sample of moist air relative to the mole fraction at saturation at constant temperature and pressure, the relative humidity is a function of the pressure and temperature of moist air, as well as its water content.<sup>4</sup> Whereas the absolute humidity can be calculated from measurements of relative humidity, temperature, and pressure, this approach has limited accuracy in practice. Other limitations of these sensors include hysteresis near saturation, insensitivity in cold, dry conditions, and slow response. Compared to other techniques, relative humidity sensors are far less accurate and stable, and cover a smaller range of humidity.

Optical absorption techniques have been used extensively for accurate measurements of atmospheric humidity, with particular success in the dry conditions of the stratosphere, where the sensitivity and selectivity of molecular absorption lines provide distinct advantages over techniques

based on chemistry. The instruments developed for this purpose, based on ultraviolet absorption at the 121.56 nm Lyman-alpha line of hydrogen, are large, complicated, and subject to short-term drifts in calibration.<sup>5</sup> Infrared optical absorption hygrometers have benefited from recent developments in solid-state lasers and integrated electronics, which have enabled a significant reduction in the mass, volume, and power of the instruments.<sup>6,7</sup> While the spectral requirements of these instruments currently make the lasers difficult to fabricate, this approach is yielding excellent data.

Concurrent to the development of optical absorption hygrometers, dewpoint/frostpoint hygrometers have been developed for and successfully employed in atmospheric measurements on airplanes and high-altitude balloons.<sup>8</sup> The particular advantage of this approach is that the thermodynamic properties of water provide a direct link between dewpoint/frostpoint and the partial pressure of water vapor in the atmosphere. As a consequence, unlike optical absorption hygrometers, dewpoint hygrometers have been employed as transfer standards for humidity measurement.<sup>9</sup>

#### DEWPOINT AND FROSTPOINT MEASUREMENT

Defined as the temperature at which gas of given composition is saturated with water vapor, assuming constant pressure, dewpoint is directly related to water vapor pressure, independent of the air temperature. For moist air, this relationship is accurately tabulated in the international steam tables. Similar tables relate frostpoint to water vapor pressure.

Measurement of dewpoint is usually accomplished by apparatus designed to approximate the saturation temperature of air containing an unknown quantity of water vapor, based on the observation that dewpoint and frostpoint correspond to the temperature at which moisture begins to condense on a cold surface under conditions near equilibrium. Chilled-mirror hygrometers cool a mirror in contact with moist air until condensation forms on the surface. Condensation is detected optically by monitoring the reflectivity of the mirror, and the temperature of the mirror is controlled to maintain an equilibrium between condensation and evaporation in the presence of changing humidity. Manufacturers of chilled-mirror hygrometers typically specify an accuracy of  $\pm 0.2^\circ\text{C}$ , although better accuracy has been reported in the literature. Using a two-stage TEC, chilled mirror hygrometers measure dewpoint/frostpoint over a range of  $-35^\circ\text{C}$  to  $25^\circ\text{C}$ . Larger systems, employing 4 or 5 stage TECs, can measure frostpoint down to  $-80^\circ\text{C}$ , and cryogenic systems have been developed which measure frostpoint as low as  $-100^\circ\text{C}$ .

With respect to balloon-borne radiosondes, the disadvantages of chilled-mirror hygrometers are cost, power, and mass. For airplane applications, the response time of chilled-mirror hygrometers is an important issue, particularly in atmospheric conditions involving a highly non-uniform distribution of water vapor. Such atmospheric conditions include microbursts, which are meteorological phenomena of enormous practical interest. There is, therefore, a need for

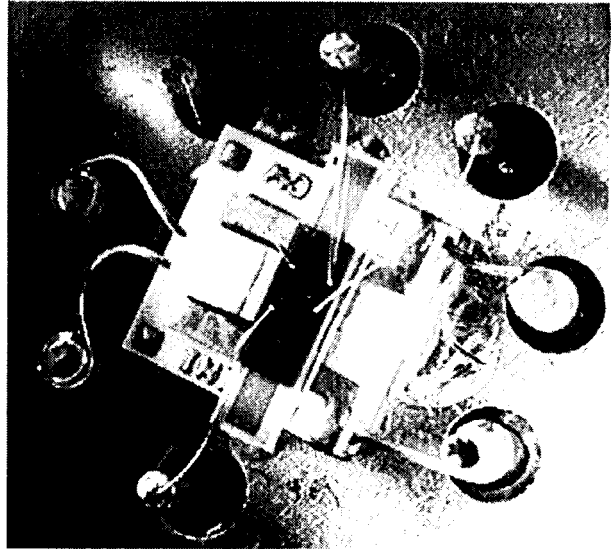


Figure 1: Photograph of the moisture sensor used in the SAW hygrometer. Interdigitated electrodes excite a resonant acoustic wave on the surface of the SAW device. The frequency of the resonance is sensitive to condensation, which serves as the basis for the sensor. The SAW device and a platinum resistance thermometer (PRT) are mounted on a two-stage thermoelectric cooler (TEC). With the SAW exposed to moist air, the TEC cools the surface until condensation is detected, while the PRT is used to measure the temperature at which condensation occurs. Because of the high sensitivity of the SAW to condensation and the low thermal mass of the sensor, the SAW hygrometer is capable of very fast response to variable humidity.

faster, smaller, and cheaper hygrometers which can accurately measure dewpoint/frostpoint.

#### THE SAW DEWPOINT HYGROMETER

We have developed a new dewpoint hygrometer which greatly improves the response time compared to conventional instruments.<sup>11,12,13,14</sup> The moisture sensor in this hygrometer uses a surface acoustic wave (SAW) device as a sensitive detector of condensation (see Figure 1). The SAW device is a quartz crystal which is designed to support high-frequency acoustic oscillations.<sup>15</sup> Because these oscillations are quite sensitive to surface effects, condensation produces a measurable shift in the resonance frequency of the SAW device. A two-stage thermoelectric cooler electronically heats or cools the SAW device, while a platinum resistor is used to monitor the temperature. The SAW hygrometer measures dewpoint by establishing equilibrium between evaporation and condensation on the surface of the SAW device. Using a SAW device as a fast, high-sensitivity moisture sensor, a feedback controller measures the condensation on the sensor surface, and responds by heating or cooling the sensor to maintain equilibrium. The equilibrium temperature under feedback control is a measure of dewpoint or frostpoint, depending on the phase of the condensed moisture.

The fact that the two methods use the same measurement principle invites a direct comparison of the performance of the SAW hygrometer and chilled-mirror hygrometers. With regard to the speed of response, the SAW hygrometer has two important advantages which are reflected in the data. The SAW device is approximately two orders of magnitude more sensitive to condensation than the chilled-mirror optical sensor. As a result, the SAW device responds to very small quantities of condensed water, which enables fast response to humidity variations. This is particularly important at low frostpoints, where condensation and evaporation are slow due to the low vapor pressure of ice at these temperatures and the low concentration of water vapor in the environment. In addition, the small size of the SAW device enables fast thermal response in the presence of varying humidity. While the thermal response time is only one component of the speed of the instrument, it represents a hard limit in the response time of condensation-based dewpoint/frostpoint measurements, and it plays an important role in determining how closely the instrument can track fast humidity transients.

The SAW hygrometer uses an uncoated SAW to measure surface-loading due to condensation, and cannot directly measure the composition of matter condensed from the atmosphere (chilled-mirror hygrometers share this limitation). For this reason, contamination is a potential source of error. Contaminants on the SAW surface can cause a shift in the oscillation frequency. Dissolved contaminants can alter the equilibrium vapor pressure of condensed water. These errors are minimized by performing a periodic self-calibration, in which the SAW is heated to evaporate condensed water and volatile contaminants, and did not appear to affect the accuracy of the SAW hygrometer data on the DC8 over the course of two months of experiments. The

effects of contamination on the SAW will be systematically tested during the course of future development.

A prototype of the SAW hygrometer was developed at JPL for testing and evaluation during FY'94-'95. In comparisons with state-of-the-art chilled mirror hygrometers both in the laboratory and on the NASA DC8 Airborne Laboratory, significantly faster response was observed using the prototype SAW hygrometer. Using a humidity generator in the JPL metrology laboratory, the prototype SAW hygrometer was directly compared with a General Eastern Model 1311XR chilled-mirror hygrometer. The two instruments were found to have comparable accuracy in steady-state conditions, but because of the faster response of the SAW hygrometer, higher-frequency response was observed in the SAW hygrometer data, and transient errors were greatly reduced. Flight tests on the NASA DC8 dramatically confirmed this result.

#### HUMIDITY MEASUREMENTS ON THE NASA DC8

The NASA DC8 Airborne Laboratory is a modified commercial aircraft used as an experimental platform for a variety of scientific projects (see Figure 2). Facility instruments on the NASA DC8 include two commercial chilled mirror hygrometers configured to sample air external to the aircraft and measure the dewpoint/frostpoint during flight. The DC8 chilled-mirror hygrometers were mounted on the forward window on the starboard side of the plane, with the mirrors as close to the inlet ports as possible. Similarly, the prototype SAW hygrometer was mounted to the forward window on the port side of the plane. The inlet lines fed directly into the sensors of the respective hygrometers, with no intervening valves or filters which could slow their response.



Figure 2: Photograph of the DC8 Airborne Laboratory at Moffett Field, California. The windows of the DC8 have been replaced with metal plates, which serve as mounting platforms for instruments used in the experiments. Inside the plane, instrument racks occupy much of the floor area used by seats on commercial aircraft. In these experiments, the SAW hygrometer was located in the first row on the port side of the airplane, while the chilled mirror hygrometers were located directly across the aisle on the starboard side of the plane.

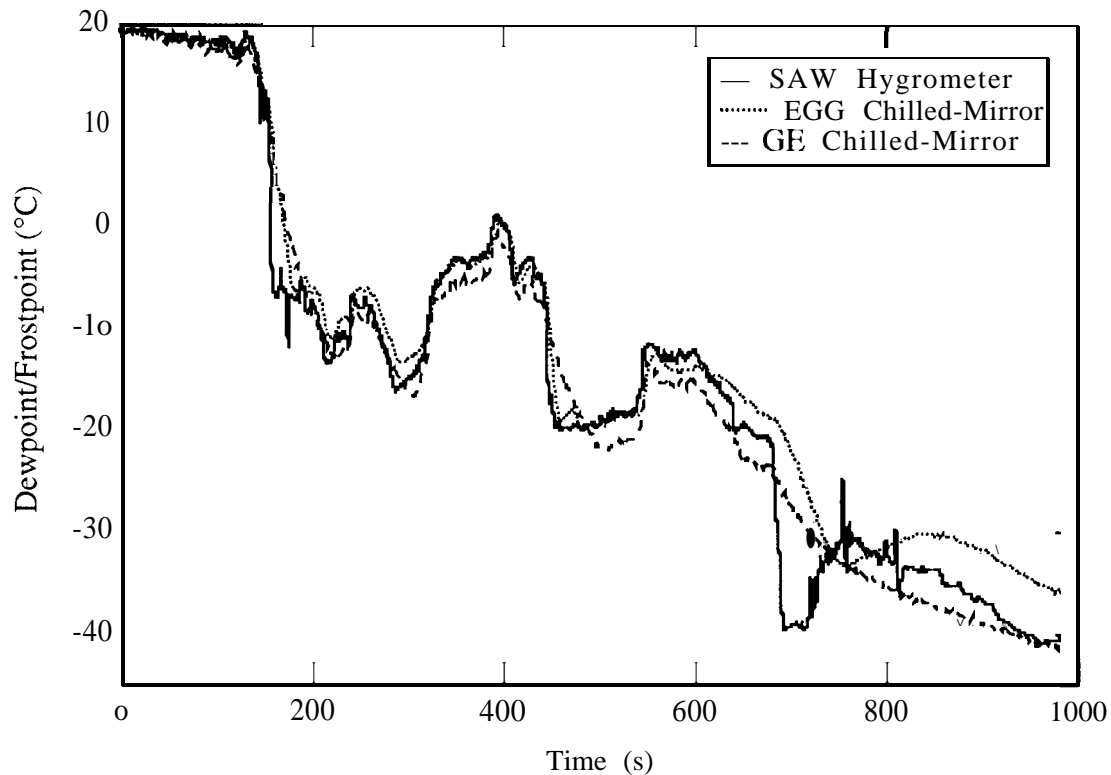


Figure 3: Humidity data from the DC8 Airborne Laboratory during takeoff and ascent on April 29, 1995, in Houston, Texas. The data from the three sensors show similar coarse atmospheric structure. The SAW hygrometer data show more short-period structure, and faster response to the large transients observed during ascent.

Data taken during the initial DC8 flights provided a useful **comparison of the performance of the SAW hygrometer** with the two chilled-mirror hygrometers. Figure 3 shows data in Houston on April 29, 1995. The three hygrometers showed good agreement with regard to the coarse atmospheric structure observed during takeoff and ascent. Detailed structure in the data reveals the differences in performance between the SAW and chilled-mirror hygrometers. The most pronounced differences occur during humidity transients and at low frostpoints. In all cases, the SAW hygrometer responded faster than the chilled-mirror hygrometers during transients. As a result, peaks and valleys in the chilled-mirror data sometimes appear to lag behind corresponding features in the SAW data, and detailed structure in the SAW data is often missing from the chilled-mirror data. Discrepancies in the chilled-mirror data were occasionally very large during humidity transients. The chilled-mirror hygrometers showed visibly slower response at low frostpoints, resulting in overshoot and large relative errors. These results demonstrate the capabilities of the SAW hygrometer to measure humidity in the troposphere, with faster response than the chilled-mirror hygrometers flown on the DC8. However, verifying the accuracy of structure in the SAW hygrometer data requires an independent measurement of humidity using an instrument at least as fast as the SAW. To fulfill this requirement, a second SAW hygrometer was installed in the NASA DC8. In order to ensure independent humidity measurements under identical conditions, the air inlet tube was split symmetrically, with equal flow to the two SAW hygrometers. Correlations

between data from two independent SAW hygrometers can be used to distinguish random **noise from signals due to** atmospheric structure. Measurements on the DC8 following this installation showed excellent short- and long-period correlations between the two SAW hygrometers. This confirms that the short-period structure in the SAW hygrometer data is representative of faster response to atmospheric humidity, as compared to the chilled-mirror hygrometers. While the factors affecting the response speed of the different instruments are non-linear and at least partly instrument-specific, it is useful to compare the responses of the various instruments to large and small transients.

Figure 4 shows data recorded by the SAW and chilled-mirror hygrometers during both large and small humidity transients during descent of the DC8 on May 19, 1995. Initially, all four hygrometers recorded frostpoint variations over the range of  $-20^{\circ}\text{C}$  to  $-35^{\circ}\text{C}$ . The SAW hygrometers reported a large number of small transients during this time, occurring over time intervals of less than a second to several tens of seconds. The chilled-mirror data clearly lag behind the SAW data, showing over- and under-shoot of the actual humidity, with an almost complete absence of short-period response. A rapid rise in the frostpoint occurred at a time of approximately 290 s in Figure 4. At the time of this event, both SAW hygrometers tracked a  $40^{\circ}\text{C}$  change in dewpoint/frostpoint over a few seconds, including a sudden  $25^{\circ}\text{C}$  rise in frostpoint during the first second of the transient. The SAW hygrometers continued to record structure

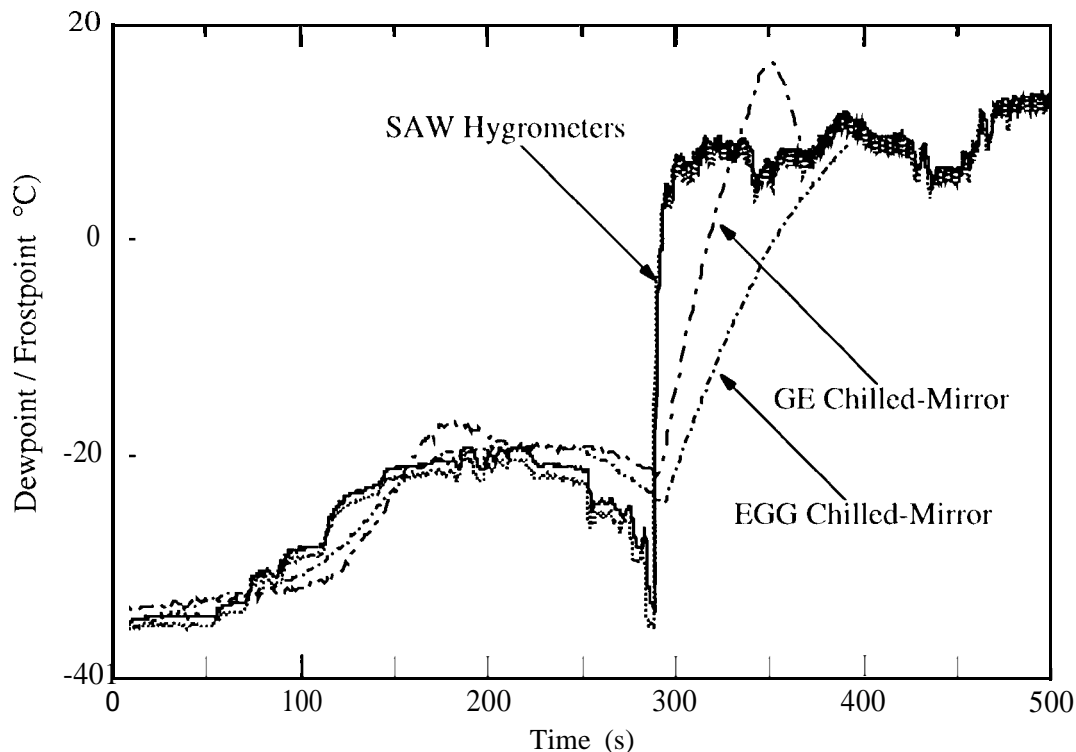


Figure 4: Humidity data taken during descent of the DC8 Airborne Laboratory on May 19, 1995. The two SAW hygrometers respond far faster than the two chilled mirror hygrometers, with correspondingly higher accuracy in dynamic conditions. Short-period structure in the SAW hygrometer data, verified by correlations between the two independent SAW instruments, is absent in data from the slower-responding chilled mirror hygrometers.

in the atmospheric humidity after the transient, while the chilled-mirror hygrometers attempted to recover from excess condensation caused by the rapid influx of warm, moist air. The GE hygrometer reported maximum heating, a status indicative of the loss of active dewpoint tracking, and ultimately overshoot the actual dewpoint by about 10°C before recovering, more than a minute after the event. The EGG hygrometer reported invalid data after the transient, and had not yet recovered when the DC8 data acquisition computer was shut off in preparation for landing, over 1.5 minutes after the event.

The SAW hygrometer has demonstrated significantly faster response than commercial chilled-mirror hygrometers in the laboratory and on the NASA DC8, while showing comparable accuracy under steady-state conditions. This **represents the potential** for a significant improvement in humidity measurement for applications that require the accuracy of direct dewpoint measurement with faster response than is possible with chilled-mirror instruments.

## SAW MICROHYGROMETER DEVELOPMENT

We are currently developing a SAW dewpoint microhygrometer, which will be much smaller, use less power, and will have improved performance, compared to the system flown on the DC8. The SAW microhygrometer will have a mass of approximately 0.3 kg (exclusive of batteries), and occupy a volume of approximately 0.5 l. The average power

consumption will be approximately 2 Watts, with a maximum of approximately 5 Watts, using a two-stage thermoelectric cooler to control the SAW temperature. The cooling power of the two-stage thermoelectric cooler provides a dewpoint/frostpoint measurement range of approximately 60°C below the temperature of the heat sink. If the heat sink is at room temperature, this corresponds to a water vapor concentration of approximately 100 ppm by volume. A larger dynamic range is possible by substituting a larger thermoelectric cooler, at the expense of additional power consumption. The reference radiosonde will be designed for maximum thermal coupling between the TEC heat sink and the atmosphere, in order to enable measurements of low values of frostpoint expected near the tropopause.

## SAW MICROHYGROMETER FLIGHT VALIDATION - REFERENCE RADIOSONDE

Flight validation tests of the SAW microhygrometer will be conducted as part of the development of a balloon-borne reference radiosonde at JPL. These tests will provide *direct in situ* comparisons of tropospheric humidity profiles obtained with commercial radiosonde hygrometers and the SAW microhygrometer. The development of an accurate radiosonde hygrometer would be of significant benefit to weather prediction and climate forecasting efforts which rely on atmospheric humidity profiles measured by radiosondes. Atmospheric scientists have been calling for improved radiosonde measurements of atmospheric humidity, citing